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INTAKE STRUCTURE OPERATION STUDY ELK CREEK DAM, OREGON

by

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Elk Creek Dam, presently under construction in the Rogue River Basin, Oregon, will be operated for multiple purposes including flood control and fish and wildlife enhancement. Flood control will dictate the quantity of water released; and fish and wildlife enchancement, the quality. Selective withdrawal will be used to control the dam's release water temperature, which is important to the anadromous fishery in the Rogue River. When selective withdrawal occurs through more than one level of intakes, the unique, single-wet-well intake structure will resemble an intake manifold in a density-stratified fluid.

To operate the structure effectively for release temperature, the site-specific characteristics of selective withdrawal and simultaneous, multiplc-level withdrawal were required. A 1:20-scale physical model of the unique intake structure and near field topography was built and tested, and the results of those tests are reported herein. The model was also employed to detect any hydraulic instabilities characterized by pressure fluctuations within

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the structure. The testing indicated no hydraulic instabilities and produced reasonable site-specific descriptions of selective withdrawal and simultaneous, multiple-level withdrawal. From these data, an existing one-dimensional mathematical reservoir model was modified to predict, from total discharge, a release temperature objective, and in-lake temperature distribution the intake gate openings that will most closely achieve the desired release temperature.

PREFACE

This report was sponsored by the US Army Engineer District, Portland, as part of a physical model study of the proposed intake structure in Elk Creek Lake, Oregon.

The study was conducted by personnel of the Hydraulics Laboratory (HL), US Army Engineer Waterways Experiment Station (WES) during the period January 1986 to March 1988. The study was conducted under the direction of Messrs. F. A. Herrmann, Jr., Chief, HL; R. A. Sager, Assistant Chief, HL; and G. A. Pickering, Chief, Hydraulic Structures Division (HSD). The tests were conducted by Messrs. S. E. Howington, J. E. Davis, and C. Buie and Ms. K. R. Ingram, Reservoir Water Quality Branch (RWQB), HSD, under the direct supervision of Dr. J. P. Holland, Chief, RWQB, and Dr. R. E. Price, former Acting Chief, RWQB. This report was prepared by Mr. Howington and edited by Mrs. Marsha C. Gay, Information Technology Laboratory, WES.

Commander and Director of WES during preparation of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square metres
acre-feet	1,233.489	cubic metres
cubic feet	0.02831685	cubic metres
degrees (angle)	0.1745329	radians
feet	0.3048	metres
feet of water (39.2° F)	2,988.98	pascals
inches	25.4	millmetres
miles (US statute)	1.609347	kilometres
square miles	2.589998	square kilometres

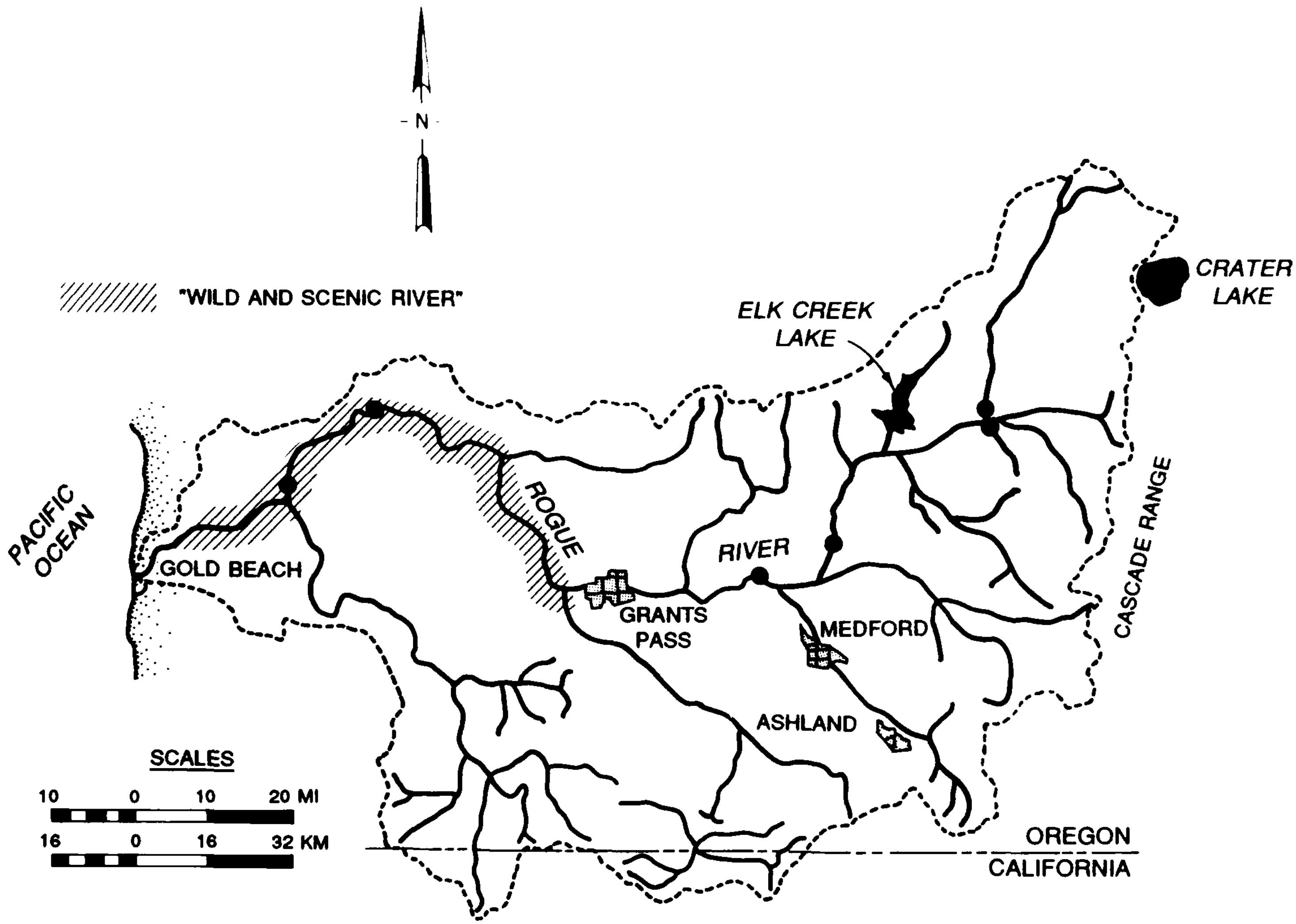

Figure 1. Location map

INTAKE STRUCTURE OPERATION STUDY

ELK CREEK DAM, OREGON

PART I: BACKGROUND

Description of the Prototype

1. Elk Creek Dam is presently under construction at river mile 1.7 on Elk Creek in Jackson County, Oregon (Figure 1). Elk Creek meets the Rogue River 5.4 river miles downstream of Lost Creek Dam and 153 river miles from the Pacific Ocean. Once completed, the dam and reservoir will be maintained and operated by the US Army Engineer District (USAED), Portland (1985).

2. The reservoir impounded by the Elk Creek Dam will have a length of about 6.2 miles,* a surface area of about 1,290 acres, and a volume of about 101,000 acre-ft, all as measured at maximum pool elevation of 1726.** The maximum depth of the reservoir will be about 246 ft and the average depth will be about 78 ft, also both measured at maximum pool elevation. Minimum conservation pool will be about el 1581 (USAED, Portland, 1983).

3. Elk Creek will provide the majority of inflow to the reservoir. Elk Creek at the damsite will drain a 132-square-mile area that constitutes about 3 percent of the Rogue River Basin (USAED, Portland, 1985). The Elk Creek subbasin consists of undeveloped, timber-covered mountains, which help comprise the western slope of the Cascade Mountain Range. The location of this drainage area relative to the mountains and the Pacific Ocean produces a climate with mild, wet winters and warm, dry summers (USAED, Portland, 1966). Based upon an average annual runoff of 209 cfs in Elk Creek at Trail, OR, for the period 1946 through 1980, the average rainfall over the basin was computed to be 20.8 in. annually (USAED, Portland, 1985). During the same 35-year period, the maximum flow recorded was 19,200 cfs and the minimum flow recorded was 0.4 cfs (USAED, Portland, 1985).

4. In 1986, construction of the 2,580-ft-long, 249-ft-high,

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

** All elevations (el) and stages cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

roller-compacted concrete dam was initiated. Its conception, however, as part of the Rogue River Basin Project, dates back to the early 1960's. This basin-wide development, including the already constructed Applegate and Lost Creek Dams, has flood control, fish and wildlife enhancement, irrigation, water supply, power generation (existing and future), recreation, and water quality as authorized purposes.

5. Outlet facilities from the Elk Creek Reservoir will consist of a water quality system for releases up to 500 cfs, a regulating outlet for releases up to 7,400 cfs (at minimum pool elevation) in excess of the water quality system, and an overflow spillway for passage of extreme flood flows. The water quality system and the regulating outlet will be located within the same concrete intake structure, shown in Figure 2, which will be mounted to the vertical, upstream face of the dam. The regulating outlet located near the reservoir bottom is to be composed of a grated intake, about 35 ft tall and 40 ft wide with an invert elevation of 1520, behind which extend two outlet conduits. These conduits will lead to a flip bucket spillway.

6. The water quality control portion of the intake structure will have a single wet well 21 ft wide by 7 ft across. For structural support, the wet well will have 1.5-ft-thick dividing walls between el 1560 and 1655 and el 1690 and 1700. Four sets of dual ports will enter the wet well at invert el 1690, 1645, 1610, and 1560. Each port will be 5 ft wide and 10 ft tall and will have a trashrack covering the intake. The ports will also have cable-hung slide gates designed with rounded bottoms allowing them to be set to partial openings. The gate slots will be open between the port levels and will be covered with trash screens.

7. At the base of the wet well, the flow must transition from the large rectangular geometry of the upper wet well to a 7- by 7-ft rectangular conduit. It then must immediately make the transition to a 7-ft-diam conduit and simultaneously change direction by about 90 deg. This conduit leads to a release manifold composed of three fixed-cone valves. Some provisions for hydropower have already been designed into the project, but plans do not presently call for the immediate completion of the hydropower facilities.

8. Operation of the release facilities will focus on the downstream aquatic environment, much as the other Rogue River Basin impoundments. The anadromous fishery downstream in the Rogue River is world renowned, and its aesthetic and economic value to the area is profound. Therefore, structure

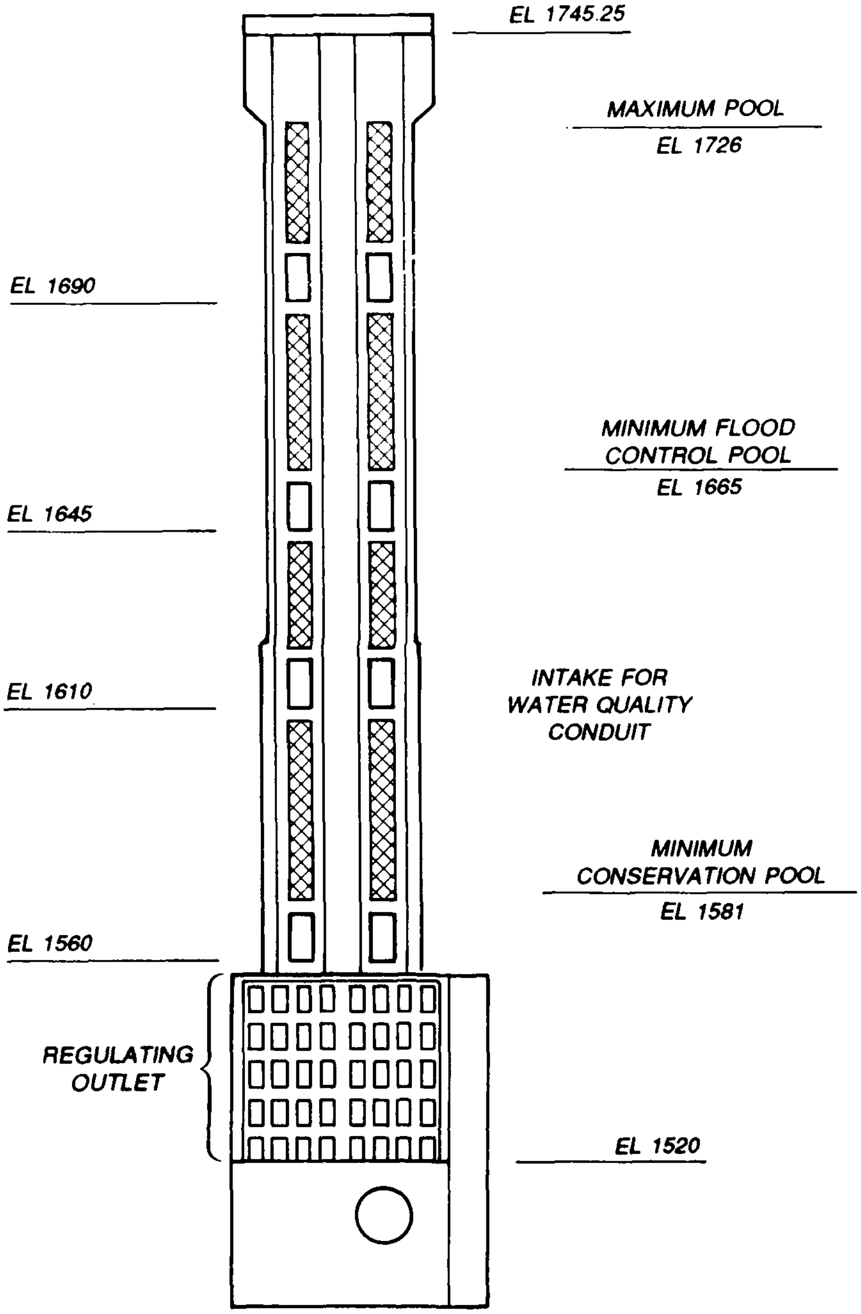

Figure 2. Elevation view of the Elk Creek Dam intake structure (from USAED, Portland, 1983)

operations will focus on the maintenance of downstream water quality most beneficial to the fishery.

Study Purpose

9. The aquatic environment downstream of the proposed dam is thought to be very sensitive to water temperature, due, in large part, to the sensitivity of the anadromous fishery (Cramer et al. 1985). Many biological functions in these fish such as egg and fish development rates, spawning, and migration are thought to be strongly dependent on water temperature (Cramer et al. 1985). Therefore, after completion of the dam, some means of control over the release water temperatures from the dam will be required.

10. The proposed technique to be used at this facility for manipulating release water temperature is selective withdrawal. This is the method of choice at the other two Corps dams in the Rogue River Basin by which thermal stratification present during the late spring, summer, and fall is used to limit the vertical range of withdrawal from the pool. From the physical properties of water, density differences exist between water of different temperatures, all other components being equal. Above 4° C (39.2° F), warmer water is lighter than cooler water. Therefore, in reservoirs, the surface waters that are exposed to an influx of thermal energy become lighter and remain at the surface. This allows the development and maintenance of stable thermal and density stratification patterns.

11. The buoyant forces associated with density differences discourage vertical movement of water. This effect often permits the withdrawal of water from a limited vertical range within the stratified pool, affording some choice among withdrawal temperatures when multiple port elevations exist and are located within different reservoir thermal strata.

12. Density stratification, which makes selective withdrawal possible, also presents potential difficulties in the operation of single wet well structures. Very often, in a situation with such stringent downstream temperature requirements as at Elk Creek, two or more simultaneous levels of withdrawal are needed. Use of any one of the individual levels of withdrawal would often not provide a release temperature close enough to the desired release temperature. When multiple levels of withdrawal are employed in a single wet well structure, density stratification can sometimes significantly

impact the release temperature by influencing the flow distribution between the withdraw l levels (Howington 1988). Effective operation of this type of structure would require that these influences be well understood.

13. A separate concern for Elk Creek Lake is the unique design of the intake structure. The possibility of hydraulic instabilities within the structure, though not considered likely, was a concern nonetheless. These concerns were increased when, for structural support, a dividing wall was proposed within the wet well. This effectively created, at low water-surface elevations, a tuning-fork-type single wet well intake structure. Concern was expressed over the potential for an oscillating motion to be established between the water surfaces in each arm of the divided wet well. At the least, this motion would pose difficulty in computing and controlling reservoi release quantities, and subsequently, release temperatures. If large enough, over time, this instability could also cause concern for the structure's integrity.

Study Objectives

14. To address these issues, a study was undertaken to examine the operational characteristics of the intake structure thoroughly. This examination evaluated the capability of the structure to produce the desired release water temperature assuming this temperature was available within the pool and was accessible with the water quality control system. The evaluation was also designed to produce accurate descriptions of the intake structure's selective withdrawal characteristics and the influences of density on the port flow distribution. These descriptions will permit prediction of the release temperature for any given structure operation scenario. This logic, when reversed, provides a means of predicting operations needed to meet release temperature targets.

15. The study also investigated the existence of any hydraulic instabilities within the water quality control portion of the intake structure. This effort focused on any oscillatory flow patterns or water surface surging within the wet well. If the flow were oscillatory, these oscillations might be transmitted through the structure in the form of fluctuations in the flow distribution among the open ports and thereby produce release temperature oscillations. Additionally, other operation and maintenance problems might be

encountered in an hydraulically unstable situation.

16. Near the outset of the study, Congressional approval of funding for the construction of the Elk Creek Dam was received by USAED, Portland. Some question existed as to the proposed intake structure's ability to withdraw from multiple levels simultaneously. Answers to this problem were required quickly so that any needed modifications of the intake structure could be designed prior to its construction.

17. The study was then split into two parts. The first phase, requiring short-term, intensive investigation, determined the ability of the intake structure to withdraw water stably from multiple levels simultaneously in a stratified reservoir. "Stably" refers to the hydraulic stability of the flow. Phase II, which was not on such a tight time schedule, dealt with the development of accurate descriptions of the simultaneous, multilevel selective withdrawal characteristics of the structure.

18. All evaluations were performed by thorough testing of a scaled physical model with Froude number similitude of the intake structure and near field topography. This type of modeling has been proven to be accurate in a multitude of applications concerning hydrodynamics and stratified flow phenomena. The resulting data were compared to an existing mathematical description of describing flow distribution in such structures.

PART II: INTAKE STRUCTURE PHYSICAL MODEL

19. An operating scale model of the Elk Creek Dam intake structure was constructed for testing the characteristics of selective withdrawal, simultaneous multiple level withdrawal (more commonly known as blending), and hydrodynamic stability within the wet well. The model scale selected was 1 ft in the model equalling 20 ft in the prototype, which resulted in a model intake structure that was slightly over 12 ft tall.

Froude Number Scaling

20. The scaling procedure for models in which gravitational forces predominantly determine the flow is based on Froude ratio similitude (American Society of Civil Engineers 1942). The scaling of model parameters is such that the Froude number, the ratio of inertial to gravitational forces, remains the same between the model and the prototype. This results in a length scaling equal to the established model scale. The resulting scaling parameters follow:

Dimension*	Ratio	Scale Relations Model:Prototype
Length	$L_r = L$	1:20
Pressure	$P_r = L_r$	1:20
Area	$L_r = L_r^2$	1:400
Velocity	$V_r = L_r^{1/2}$	1:4.47
Discharge	$Q_r = L_r^{5/2}$	1:1,789
Density Difference	$\Delta p_r = 1$	1:1

* Dimensions are in terms of length.

21. While the Froude number similitude of the model and prototype was maintained, transitional to turbulent Reynolds numbers (this number being the ratio of the inertial to viscous forces in the fluid) within the model intake structure were required. Although prototype Reynolds numbers will be significantly larger than those encountered in the model, accurate assessment of energy losses and hydrodynamic stability is possible, as long as nonlaminar

flow is maintained in the model. This requirement dictated the chosen model scale of 1:20. For the selective withdrawal testing only, a much smaller model would have sufficed. Selective withdrawal models are normally scaled between 1:40 and 1:100.

22. Since it is almost impossible to replenish density-stratified fluid during a test while not disturbing the stratification patterns significantly, each test must rely entirely on the stored volume in the simulated reservoir. For this reason, the surface area and volume of the flume were necessarily large. A large surface area is required to limit water-surface drawdown during each test. No testing flumes of the required size were available at the US Army Engineer Waterways Experiment Station (WES). Therefore, a water storage sump had to be modified for use as a test flume. No covered or indoor sumps existed with the necessary depth and area. Further, funding to construct such a facility was unavailable.

23. The sump, located outside and uncovered, is schematized in Figure 3. As part of this model study, several modifications to the sump were required before it was usable as a test flume. A concrete pad to support pumps and release-water storage tanks was placed and a gravel area for truck access during inclement weather was installed. Extensive pipe work, pumping facilities, and electrical fixtures were also installed.

Intake Model Features

24. The model of the Elk Creek Dam intake structure was a 1:20-scale representation made of Plexiglas. The use of Plexiglas provides multiple benefits. It is transparent for viewing purposes and provides very smooth surfaces. When the roughness of formed concrete, as would be encountered in the prototype, is scaled to model dimensions, the model surfaces need to be very smooth to produce the appropriate frictional resistance (American Society of Civil Engineers 1942).

25. The model had individually operable intake ports. Special care was taken to represent the curvature of the edges of the intakes and the gate and gate slot dimensions. The trash bars proposed for the entrance of each water quality intake were scaled and constructed of brass. The screen, which will prevent debris from entering the gate slots, was included in the model and was represented by a fine brass screen. The model limits extended from the crown

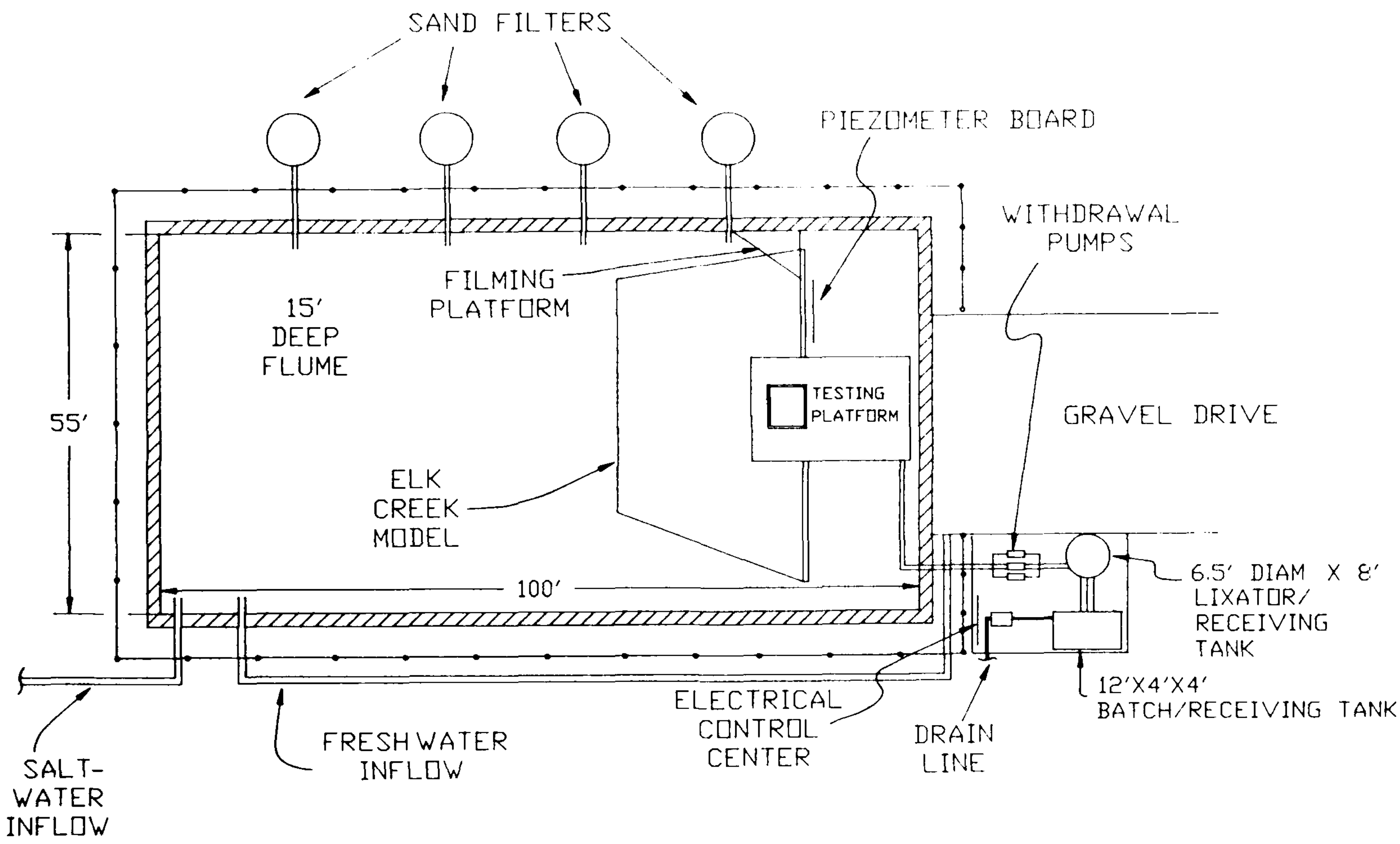

Figure 3. Plan view of the test flume

piece that will house the gate hoisting mechanisms in the prototype to the bottom of the regulating outlet entrance. The regulating outlets were modeled only a short distance into what will be the dam structure since operation of these devices was not the subject of the investigation. The water quality system was modeled through the transitions and to the exit manifold that will contain three free-discharge valves: one 18-in.-diam and two 24-in.-diam valves. These valves were modeled with polyvinylchloride ball valves, one 1-in.-diam and two 1.25-in.-diam valves. These valves were the points of flow control for the structure.

26. The intake structure model included a removable divider wall in the wet well. This wall, which had been included in the prototype design for structural stability, was theorized as a potential cause for hydraulic instability. If any hydraulic instabilities were observed during the course of the model investigations, modification of the divider wall was designated as the starting point in trying to eliminate the instabilities. Alternative designs including holes in the divider wall were also proposed for evaluation if necessary.

27. The near field topography in the vicinity of the intake structure was modeled to assess its impact on selective withdrawal characteristics accurately. Previous selective withdrawal modeling experience has indicated that topographic influences are limited laterally to twice the withdrawal zone thickness. Since the maximum withdrawal zone thickness is the maximum pool depth, the topography needed to be modeled outward about twice the maximum depth, or about 20 model feet. This part of the model was constructed with marine plywood. The topography was divided into small areas that could be approximated with flat surfaces. The topography modeled represented the most recent earthwork proposals available.

28. The vertical dam face was also represented in the model with marine plywood. All plywood structures were anchored to the concrete floor to prevent their floating. The resulting physical model is shown in Figures 4 and 5. A platform over the structure was installed for access and was never submerged during testing. Black cord was run between the intake model and the edge of the topography at 10-ft (prototype) intervals vertically for reference.

Figure 4. Elk Creek model

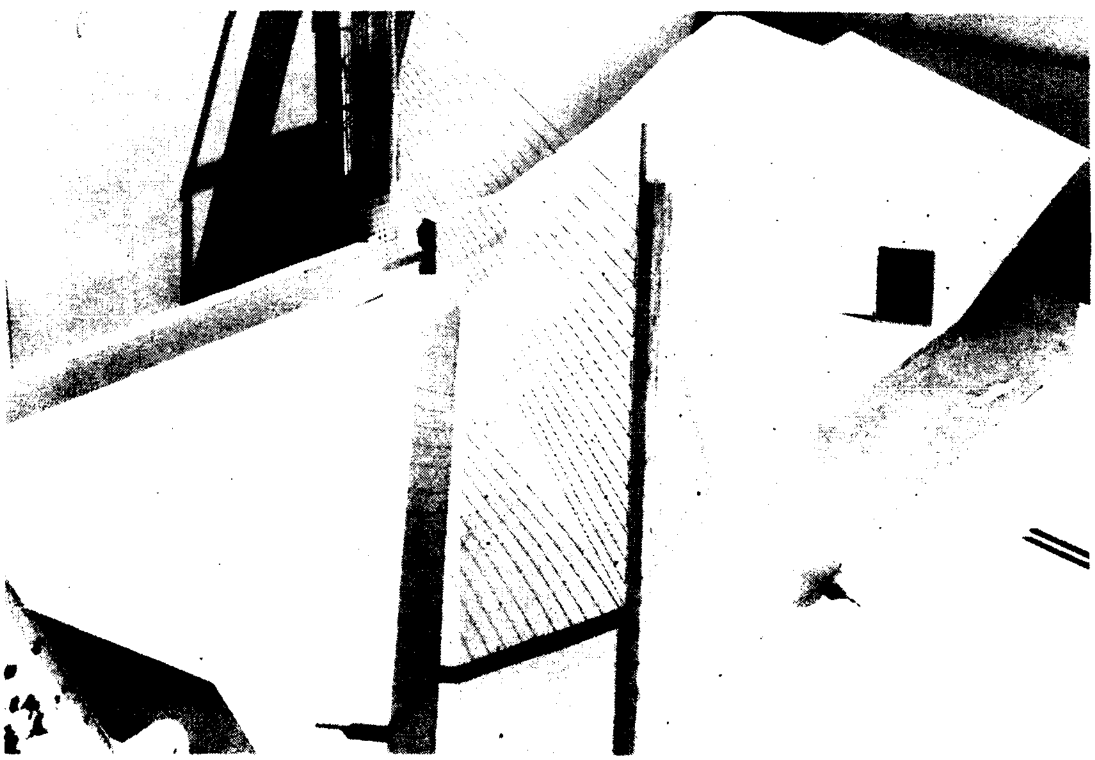

Figure 5. Elk Creek model showing topographic detail

Flow Measurement

29. Flow was removed from the flume through the water quality system with a series of withdrawal pumps in parallel (Figure 3). On the downstream side of these pumps, the pipes were fitted with saddles for use with SIGNET paddle wheel flowmeter sensors. These meters were factory calibrated for use on specific pipe sizes with a prescribed length of straight pipe upstream and downstream of each sensor to ensure symmetric velocity profiles in the pipes. The sensors were wired to digital readouts. The water being removed from the flume was stored in temporary facilities (Figure 3) until the test was concluded. At that time, the water was released slowly back into the flume or disposed.

Flume Additions and Modifications

30. As stated earlier, several additions were required to make the sump acceptable as a testing flume. As constructed, the sump was merely a concrete-lined pit. No piping or pumps had been installed. Extensive piping from freshwater lines and the salt mixing facilities, and between the pumps, the model, and the storage facilities was installed. Several pumps were installed. A control center for localized operation of the pumping network was also installed.

31. To maintain the clarity of the water, water from the City of Vicksburg was used. Even so, algae were a significant problem in the outdoor flume. Four sand filters, extensive chlorination, and pool covers were employed to help control the algae. During periods of testing under stratified conditions, the filters were turned off and algae were quickly established in the pool. This problem limited the testing window to about 2 days without mixing and restarting the stratification process. The pool covers also aided in reducing the amount of wind mixing.

PART III: PHASE I INVESTIGATION

32. Phase I of the study, conducted from January to April 1986, was designed to provide quick answers to specific yes-or-no questions: "Will the structure permit simultaneous multiple-level withdrawal from a stratified pool in the approximate flow ratios (blending) and total discharges desired?", and "Does the proposed design create any hydraulically unstable conditions?" Answers to these questions were needed to permit construction of the intake structure to continue as planned. Development of detailed descriptions of the withdrawal processes was not required at this time since this information was not relevant to the immediate questions in this phase of study.

Blending Evaluation

33. At many Corps of Engineers reservoirs, selective withdrawal through one port level at a time produces release water temperatures close enough to the downstream target temperatures to maintain the downstream environment. As previously mentioned, the release water from Elk Creek Dam will flow into the Rogue River, which is habitat for a very valuable anadromous fishery. These fish are thought to be sensitive to small deviations in temperature during critical periods of the year (Cramer et al. 1985). For this reason, the use of one level of selective withdrawal ports at a time will probably not be adequate at all times for this structure. However, the use of multiple intakes in a single wet well structure such as Elk Creek is subject to influence by density stratification (Howington 1988). The pool density pattern may significantly affect the flow distribution between the withdrawal levels, thereby affecting the release water quality. The evaluation presented by Howington (1988) was designed to provide a means of predicting these density influences and to produce operational guidance that would permit the selection of ports and port openings that would best meet the prescribed target temperatures.

Concurrently developed theory

34. Research in the area of simultaneous multiple level withdrawal from stratified reservoirs (blending) was conducted concurrently with the Elk Creek study. This work was being performed at WES under the Water Quality Research Program, funded by the Headquarters, US Army Corps of Engineers. As discovered during this work, when multiple levels of ports are open upstream of a

single point of flow control (as in a single wet well reservoir intake structure), the manner in which the total discharge is distributed among the open ports may be significantly dependent on the density stratification in the pool (Howington 1988).

35. In the most severe case, flow through one or more open ports may be effectively blocked by the buoyant forces associated with the different water densities; this is termed density blockage or buoyancy blockage. This situation, most commonly associated with strong stratification and low discharges, occurs when the hydraulic losses encountered by flow entering the intake structure are insufficient to overcome the potential energy of the density differences between the pool and the wet well. When the two opposing components, hydraulic losses and buoyancy (potential energy) are equal, the system is at a critical equilibrium. The discharge at which this equilibrium occurs is known as critical discharge. Any discharge greater than critical discharge will induce flow through the previously blocked intake port, but the distribution of flow among the open ports may still be significantly different from that to be expected in a homogeneous density environment.

36. The results of the research in the area of blending included an algorithm that can compute the distribution of flow among open ports based upon the total discharge, the open port elevations, the wet well outlet elevation, a description of the individual port loss coefficients (that were developed for Elk Creek using the physical model), and a quantified potential energy of the density stratification (known as the density impact term or buoyancy head) for each open level of withdrawal. The density impact term is approximately described by the area shaded in the hypothetical example in Figure 6. In the figure, points 1 and 2 are at the center-line elevations of the upper and lower ports, respectively. Points 1 and 2 are at the elevations containing the composite densities withdrawn through the upper and lower ports, respectively. The composite withdrawal density is simply the density of the assumedly fully mixed water entering each port. The density impact term is a measure of the additional head, due to density stratification, available to "push" water through each port level.

37. The highest open port (identified as level 1) is considered a datum with the density impact term being zero. This carries with it the assumption that the density stratification of the water in the wet well above the highest port is the same as the water in the pool above the highest port. The

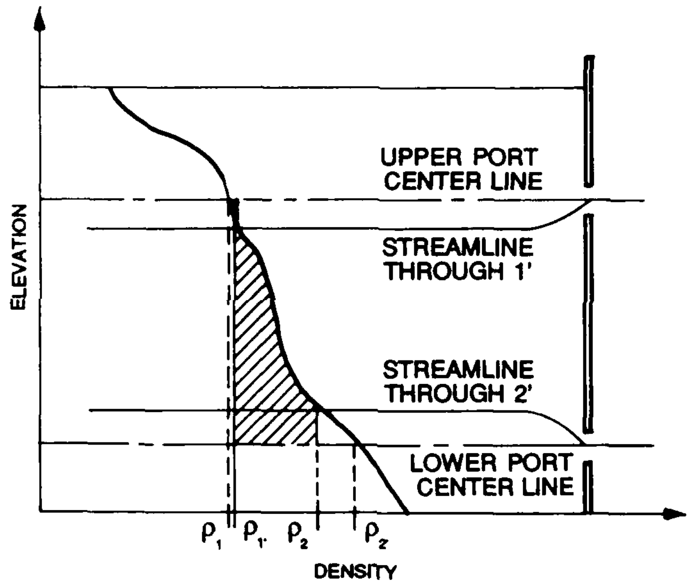

Figure 6. Example of density impact terms (Howington, in preparation)

remaining density impact term is computed as follows:

$$DIT_i = DIT_{i-1} + \frac{1}{\rho_i} \int_{i-1}^{i} [\rho(z) - \rho_w]\, dz \tag{1}$$

where

DIT_i = density impact term at port level i , ft

DIT_{i-1} = density impact term at port level $i-1$, ft

ρ_i = density entering port level i , slugs/ft^3

$\rho(z)$ = density as a function of depth, slugs/ft^3

ρ_w = density of water in the wet well between port levels i and $i-1$, slugs/ft^3

z = depth, ft

38. In the figure, the density impact term for the lower port would equal the density impact term for the upper port 0 plus the shaded region divided by the density entering the lower port $\rho_{2'}$. The shaded region in Figure 6 would equal the integral in Equation 1 with ρ_w being $\rho_{1'}$. The significance of these terms is that, if the sizes and loss coefficients of both port levels were equal, in a homogeneous density pool (all density impact terms being zero) the release flow would be split approximately evenly between the two ports. However, the density impacts shown in the figure from the

stratification would force more flow through the lowest port level than through the upper port level.

39. The algorithm discussed herein treats the density impact term much as an available head loss for each port elevation. The basic equation within the algorithm for computing the flow distribution among the open ports is given in Equation 2 (Howington 1989). The equation is essentially a summation of the individual port flows, which are determined by minimizing the total head losses in the system.

$$Q = \sum_{i=1}^{n} \sqrt{\frac{(DH + DIT_i) * 2g}{k_i * A_i^2}} \tag{2}$$

where

Q = total discharge (controlled by downstream service gate), cfs

n = number of open ports

DH = water-surface differential between the wet well and the pool, ft

g = acceleration due to gravity, ft/sec^2

k_i = head loss coefficient for port level i

A_i = area of port i, ft^2

Model testing procedures

40. The physical model of the intake structure described in Part II was used in the evaluation of simultaneous multilevel withdrawal (blending). As discussed earlier, the purpose of this part of the investigation was to determine whether or not water would be withdrawn through multiple port levels and blended into the single wet well intake structure appropriately. To expedite testing, USAED, Portland, provided a list of the most likely flow distribution percentages among the open ports for given stratification strengths. This list, in order of priority, is given in the following tabulation. The relative stratification strengths in the tabulation are referenced to the nearby Lost Creek Lake. "Strong" refers to a typical July or August stratification at Lost Creek; "moderate," a May or June stratification; and "weak," an April or October stratification. USAED, Portland, specified that the most common discharge to be used, assuming a summer season starting with a full pool, was 200 cfs and that only two levels of ports will be used simultaneously.*

* Personal communication, 18 February 1986, with Mr. Dick Cassidy, Environmental Engineer, USAED, Portland, Portland, OR.

Priority	Port Flow, %		Stratification Strength
	Upper	Lower	
1	80	20	Strong
2	70	30	Strong
3	20	80	Weak
4	30	70	Moderate
5	50	50	Strong

41. The easiest means of determining the occurrence of blending were visual observations and measurement of the release water characteristics. Preliminary tests were conducted during which no numerical data were collected. During these tests, the pool was arbitrarily stratified as in the selective withdrawal testing. Two port levels were opened and discharge was initiated. Crystalline dye was dropped at irregular intervals both inside and outside the wet well. This permitted visual inspection of the flow. From these tests it was easily seen that flow entered the wet well through both levels of open ports.

42. The information gained by visual inspection was valuable but did not demonstrate that the desired flow distribution percentages could be achieved. Measurement of the release water characteristics, coupled with dye streaks to assure multilevel flow, provided a simple means of determining the flow distributions by mass balance decomposition. When the discharge, the release value of a conservative constituent (density due to salinity in this case), and the values of that constituent entering each of two open ports were known, the flow distribution between the two ports was approximated by a straight-forward calculation.

43. To prove that the flow distributions desired were attainable, the port settings (percentage of gate openings) that would produce these distributions were needed. Accurate determination of these gate openings to achieve the desired flow distributions was identified as part of the Phase II testing to be conducted under less intense circumstances. For these tests, it was deemed satisfactory to prove that flow distributions near to and on either side of those identified in paragraph 40 could be achieved. Toward that end, nine sets of tests were conducted. Table 1 outlines the tests.

44. In Table 1, the calculated port temperature represents the upper port temperature found by assigning a lower port temperature of 4° C and using the temperature-density relationship for water to estimate an appropriate

Table 1

Phase I Blending Tests

Test Set No.	Total Flow cfs	Pool Surface Fl	Calculated Port Temperature, °C	Pycnocline El Range ft	Lower Port El	Upper Port EL
1	200	1,716	17.5	1610–1620	1,565	1,695
2	200	1,715	19.5	1661–1681		1,695
3	200	1,713	17.5	1679–1713		1,695
4	200	1,705	21.5	1655–1681		1,695
5	250	1,655	18.5	1597–1627		1,615
6	200	1,655	18.5	1597–1627		1,615
7	150	1,655	18.5	1597–1627		1,615
8	100	1,650	18.5	1607–1647		1,615
9	50	1,650	18.5	1607–1647		1,615

upper port temperature. The pycnocline range shows the lower and upper limits of the sharp density gradient that corresponds to the temperature gradient in reservoirs. As is evident from the table, the tests comprised multiple discharges, stratification strengths, water-surface elevations, and port combinations. The stratification strengths correspond well with observed strong, medium, and weak stratifications at nearby Lost Creek Lake.

45. Within each testing sequence, the lower ports were incrementally throttled in tandem to achieve different flow distributions. Testing at higher discharges was not required since the influences of density, which were the subject of these tests, had proved to be more pronounced at lower flows (Howington 1988). Figure 7 shows results from Test 9 as defined in Table 1. The horizontal axis represents the percent gate opening for the lowest ports. The vertical axis represents the percentage of the total structure discharge passing through the lower ports. Dashed lines shown in this figure are the percentage flow distributions identified in paragraph 40. Similar plots for the remaining eight tests can be found in Figures 8 and 9.

46. The maximum lower port setting for which blending was evident is shown in Figure 7. When the lower port percentage of the total discharge was 100, density blockage was present. For this example, density blockage occurred for lower port settings of 70 and 90 percent. The critical discharge

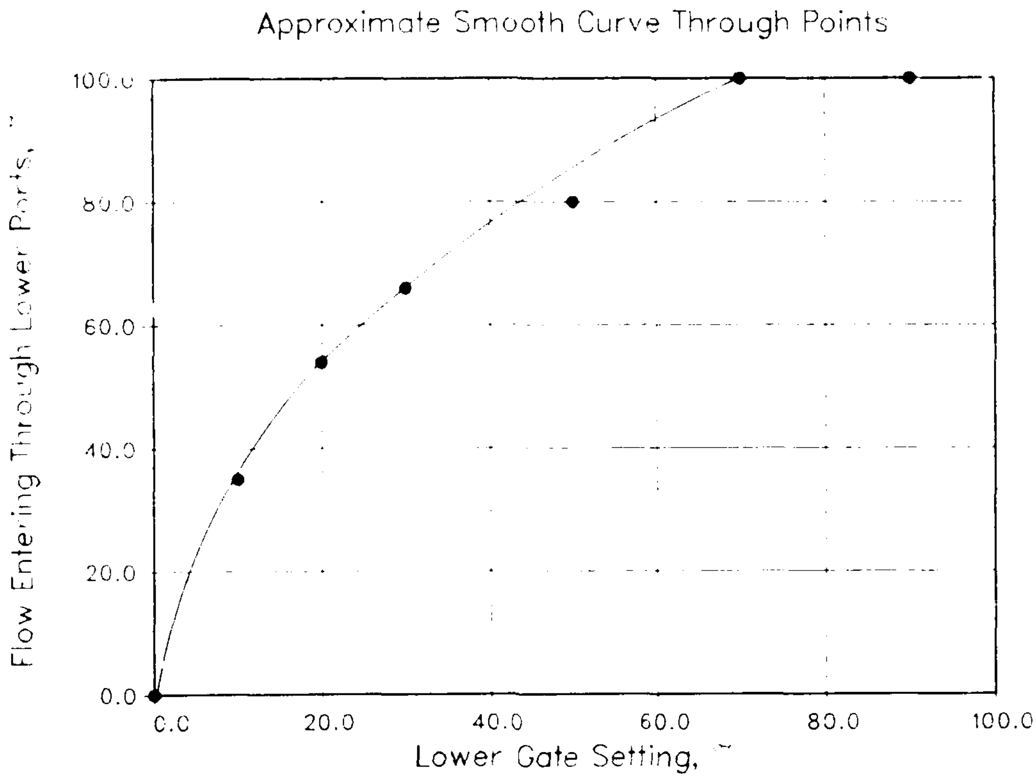

Figure 7. Blending results for Test 9

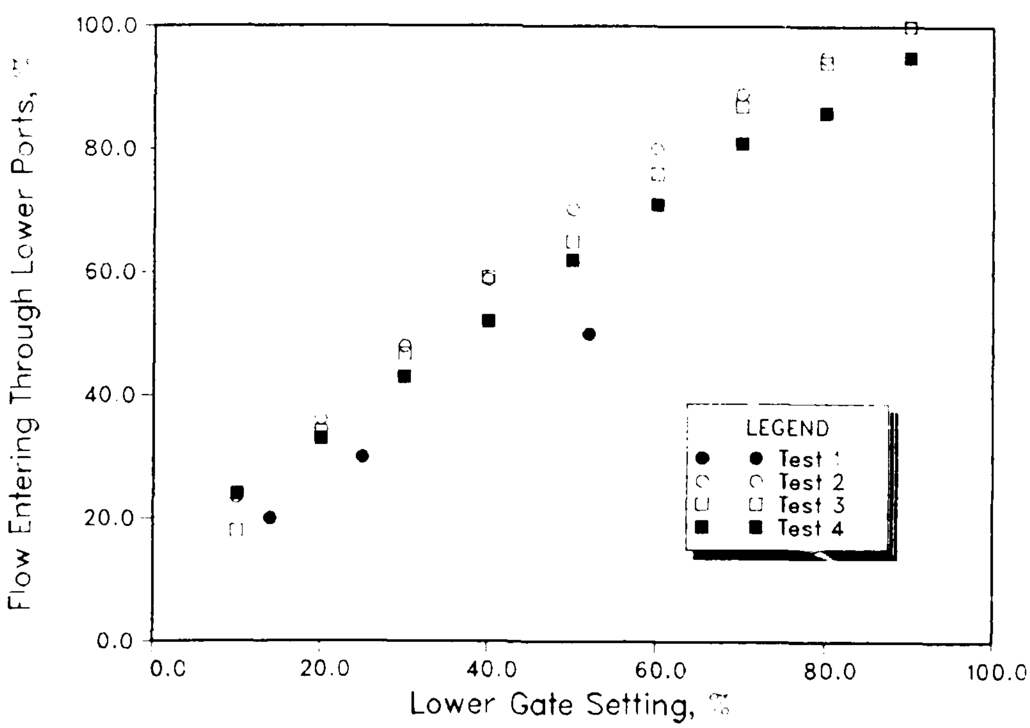

Figure 8. Blending results for Tests 1-4

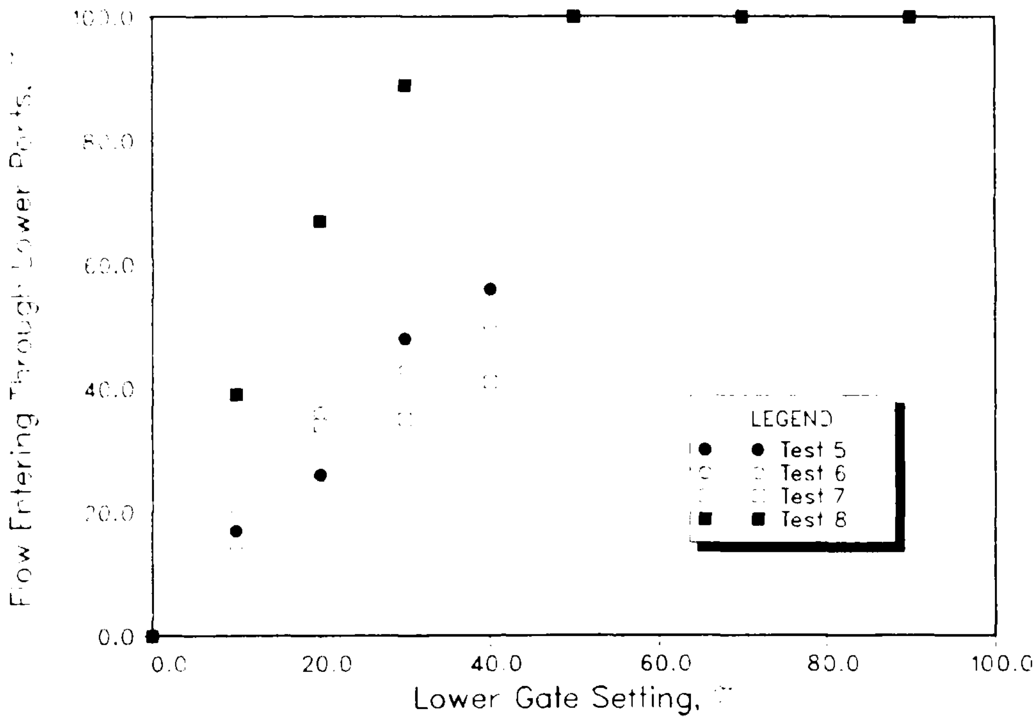

Figure 9. Blending results for Tests 5-8

for these circumstances is 50 cfs at some gate setting between 50 and 70 percent. This is evident since blending occurred at 50 percent but blockage was observed for 70 percent and above. For each test, the graph of total discharge versus lower port flow demonstrated a high degree of smoothness; that is, smooth curves could be placed through the points, indicating no discontinuities in the graphs except at critical discharge. This fact permits the confident interpolation of results between data points. These points also fell along curves that were anticipated from previous blending work (Howington 1988). From these behavioral trends, it was concluded that with the proper port settings, the desired proportionment of discharge could be achieved.

47. From the Phase I tests, simultaneous multiple level withdrawal from a density-stratified pool occurred and was, at least visually, stable. Density blockage was observed to occur, as expected, with the larger lower port openings. It was, also expectedly, more prevalent at the lower total discharges. Density blockage was easily overcome for any discharge and any stratification tested by employing the ability to partially close the ports. This feature of the ports also permitted control to be established over the flow distribution when density blockage was not a concern. The predictability

of the test results indicated that, with the appropriate port settings, the desired flow distributions could be achieved.

Hydraulic Stability Investigation

48. Hydraulic stability was a concern insofar as it might affect the release temperatures or cause undue operational or maintenance problems with the intake structure. Very low or oscillating pressures in the outlet structure might cause difficulties. Another concern was the potential for hydraulic blockage. This phenomenon, although never observed, was presented as a potential concern by Howington (1986). This would theoretically occur when the velocity jet issuing from the lower port into the single wet well structure would create an area of turbulence that would cause flow through the upper port to be effectively cut off.

Testing procedures

49. Evaluation of these potential problems was performed using two techniques: (a) visual inspection of dye movement, and (b) monitoring of pressures through a series of piezometers. During each of the blending tests discussed in the previous section, crystalline and liquid dyes were placed inside and outside the wet well at irregular intervals. The dye served a dual purpose. As mentioned earlier, it demonstrated, even under very low velocities, whether or not blending was occurring in the wet well. Also, careful observation of the dye and of the water-surface elevation in the wet well during these tests would have exposed substantial fluctuations in the velocities of the water entering the ports.

50. An additional testing sequence was performed specifically to evaluate the potential for hydraulic blockage. The conceivably worst case was considered to be the largest flow through the smallest opening for the lowest ports when the water surface in the wet well was confined to one side of the divider wall. The sequence tested was performed at the capacity for the water quality system (500 cfs, prototype), and at half the capacity for several port settings. These tests were conducted under homogeneous density conditions since the problem being examined was a purely hydraulic one.

51. As stated, the model was tapped for pressure at 67 places in the outlet structure. These taps consisted of a small hole (1/8 to 1/16 in. in diameter) to which a fitting and Tygon flexible tubing were attached. The

tubing was concealed from the flow by placing it either behind the model or within the model's hollow shell between the outer walls and the wet well walls. The other end of the tubing was connected to glass tubing mounted vertically on a board marked for vertical reference which, in turn, was mounted on the back of the model dam. This configuration differed from traditional piezometer board in that it was located in the pool. Reading the pressures was necessarily performed by underwater camera. The pressures that registered on these tubes were relative to the normal hydrostatic pressure head. The approximate locations of the pressure taps are given in Plate 1. The regulating outlet entrances were tapped for pressure, even though their use was not anticipated, since it would have been very difficult to place these taps, if they had been needed, after the model was completed.

Results

52. The results of this part of the investigation indicated no hydraulic instabilities. At no time was flow entering the ports observed to oscillate. The only oscillatory motion observed in the wet well was associated with the long-period waves in the test flume; that is, no oscillations occurred within the wet well that were not also occurring outside the well.

53. Results from the piezometer observations also indicated no oscillatory motion. An example of the pressures observed during one test are given in Figure 10. This test was conducted at a prototype flow of 500 cfs with both ports at el 1615 fully open. The horizontal axis in this figure represents the assigned pressure tap number (Plate 1). The vertical axis represents the difference, measured in feet of water converted to prototype dimensions, between the pressure measured at the tap and the hydrostatic pressure. All pressures were less than or equal to the hydrostatic pressure. The positive notation in the figure was used for convenience. Most of the pressure differences were small. Only a few exceeded 1 ft. The largest differences (tap numbers 1, 2, 8, and 16) were all located within the conduit transition region at the base of the wet well, as would be expected (Plate 1). The largest difference (tap 8) was located on the inside of the 90-deg bend in the release conduit. No periodic motion of any magnitude or frequency was observed in the piezometers during any of the tests. All taps numbered 43 and higher were unsubmerged for the data shown in Figure 10.

54. No recommended changes to the structure were identified as a result of this testing, including the retention of the divider wall. This wall,

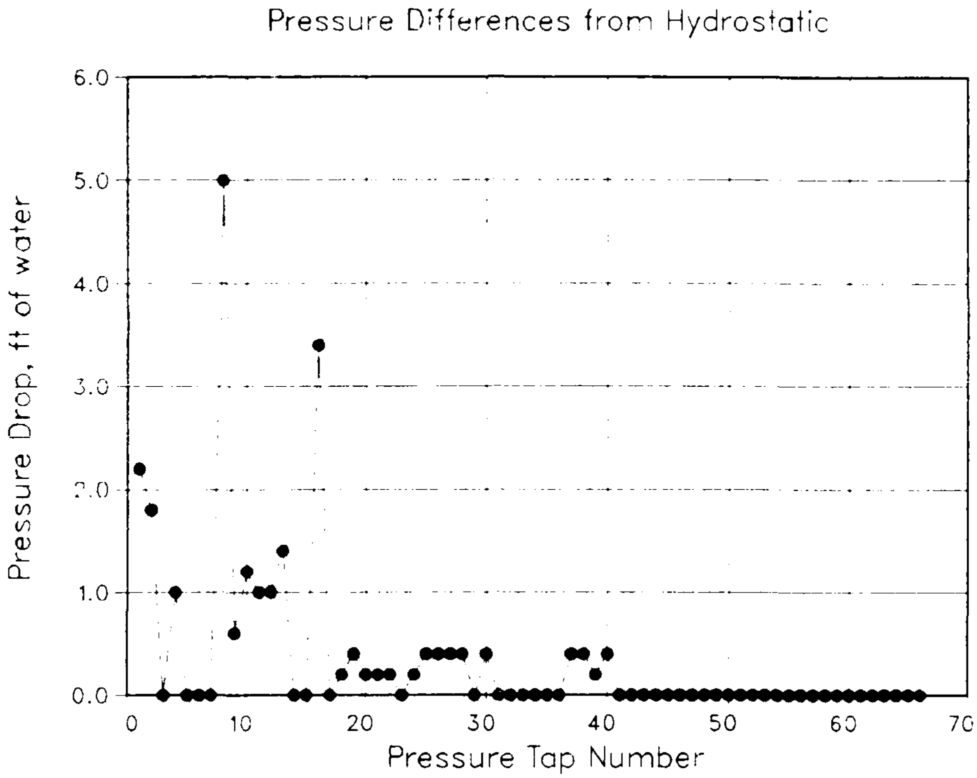

Figure 10. Pressure differences

under certain, unusual conditions, appeared to influence the avenue taken by the upper port flow, but did not appear to cause any undesirable hydraulic conditions. When both uppermost ports and only one lowermost port were open, all flow from the upper ports was observed, using dye streaks, to pass down the side of the divided section of the wet well without an open port.

PART IV: PHASE II INVESTIGATION

55. The Phase I investigation had revealed that blending in the Elk Creek structure was, indeed, possible and that the structure performed satisfactorily from a hydraulic viewpoint. The remaining work in this study was to describe the withdrawal characteristics thoroughly and provide operational information about the structure. The results of these investigations were not required to proceed with the construction of the intake structure. A thorough description of withdrawal characteristics for this type of structure required that two areas be investigated in detail: selective withdrawal and simultaneous multiple level withdrawal. Phase I had proven that simultaneous multiple level withdrawal would occur in this structure; now it had to be accurately quantified.

Selective Withdrawal

56. To maintain control of the water temperatures to be released from the Elk Creek Dam, the use of selective withdrawal (Smith et al. 1987) is proposed. Selective withdrawal is a common method for release and in-reservoir water quality maintenance that makes use of the density stratification within the pool to permit the selection and release of a particular quality of water. The density stratification serves to confine the region vertically within the reservoir from which water is withdrawn. This region is referred to as the withdrawal zone.

Historical perspective

57. It has been substantiated that most reservoir intake structure ports, although consisting often of considerable cross-sectional area, usually act as point sinks (Smith et al. 1987). A significant body of work exists on the behavior of these assumed point sinks in a vertically density-stratified fluid such as a thermally stratified reservoir. The withdrawal of water through these types of ports from a stratified reservoir produces, at some distance away from the intake port, an essentially unidirectional velocity profile in the longitudinal-vertical plane as seen in Figure 11. This velocity profile, whose magnitude and shape depend substantially on the stratification pattern in the fluid, can be used to predict the contribution made by any horizontally oriented strata in the reservoir to the withdrawn water quantity. This knowledge leads directly to the predictability of release water quality

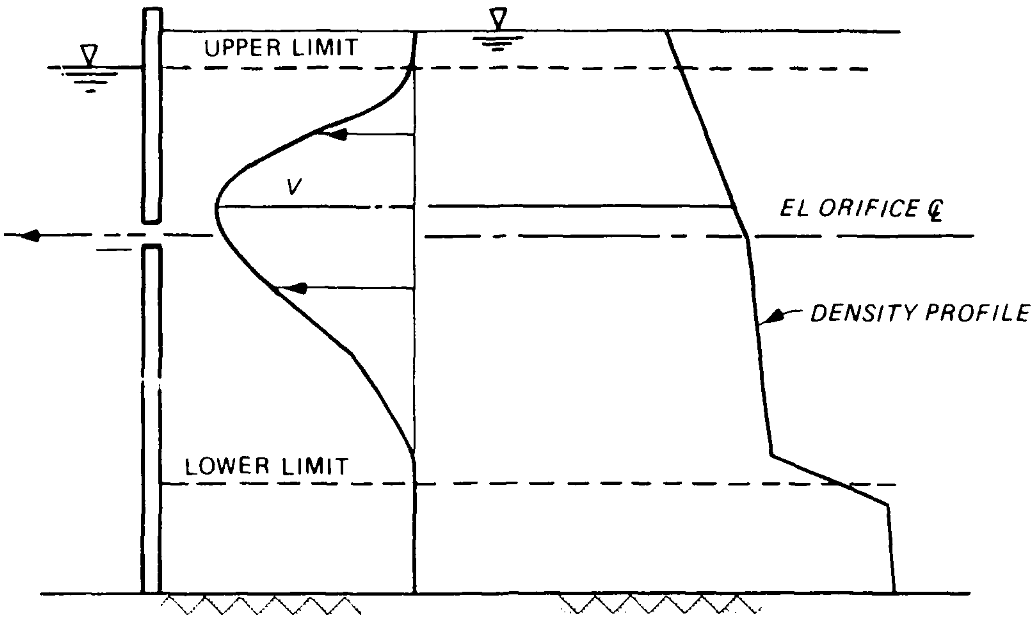

Figure 11. Example vertical velocity profile

characteristics such as density, temperature, and other vertically stratified water quality components.

58. Original work by Bohan and Grace (1973) proposed methods for relating the magnitude and shape of the velocity profile to density stratification and flow rate through the intake port (two normally obtainable pieces of information). This yielded a means of predicting the release water quality characteristics from a port by simply knowing the vertical distributions of the water density and the desired water quality constituent, the port elevation, and the discharge. Equation 3, developed by Bohan and Grace, permitted computation of the upper and lower limits of withdrawal, which described the vertical extent of the velocity profile generated by the port operation.

$$\frac{Q}{Z^3\sqrt{\frac{g}{Z}\frac{\Delta\rho}{\rho}}} = 1.0 \tag{3}$$

where

Q = flow rate, cfs

Z = elevation difference between the port center line and the upper or lower limit of withdrawal, ft

$\Delta\rho$ = fluid density difference between the port center line and the upper or lower limit of withdrawal, pcf

ρ = fluid density at the port center line, pcf

59. This approach was later found to have applicability only for those withdrawal zones (vertical range between the limits of withdrawal) that did not intersect either the water surface (upper boundary) or the reservoir bottom (lower boundary). Equation 3 was also found to be less accurate for those ports with near field topography unlike the original test conditions that consisted of an orifice in a vertical, flat plate. The description for selective withdrawal has since been updated to account for both boundary interference and near field topographic influences. The most recent selective withdrawal equations for flow through a port are given by Smith et al. (1987) to be

$$\frac{Q}{Z^3\sqrt{\frac{g}{Z}\frac{\Delta\rho}{\rho}}} = \frac{\theta}{\pi} \tag{4}$$

and

$$\frac{Q}{D^3\sqrt{\frac{g}{D}\frac{\Delta\rho}{\rho}}} = \frac{\theta}{2\pi}\,\frac{1 + \frac{1}{\pi}\sin\left(\frac{b/D}{1 - b/D}\right)^{\pi} + \frac{b/D}{1 - b/D}}{\left(1 + \frac{b/D}{1 - b/D}\right)^{3}} \tag{5}$$

where

θ = effective angle of withdrawal, radians

π = 3.14159 radians

D = distance between the boundary of interference and the free limit of withdrawal, ft

b = distance between the center line of the outlet and the free limit of withdrawal, ft

$\Delta\rho$ = fluid density difference between the boundary of interference and free limit of withdrawal, pcf

60. The effective angle of withdrawal θ in both Equations 4 and 5 is the means by which the descriptions account for topographic influences. A completely unobstructed intake, closely approximated by a vertical pipe in the center of a deep water body, would withdraw water from 360 deg in plan view. The effect of a topographic influence is to confine the withdrawal laterally resulting in a vertical expansion of the withdrawal zone compared to the completely unobstructed intake. Example withdrawal angles are given in Figure 12 taken from Smith et al. (1987).

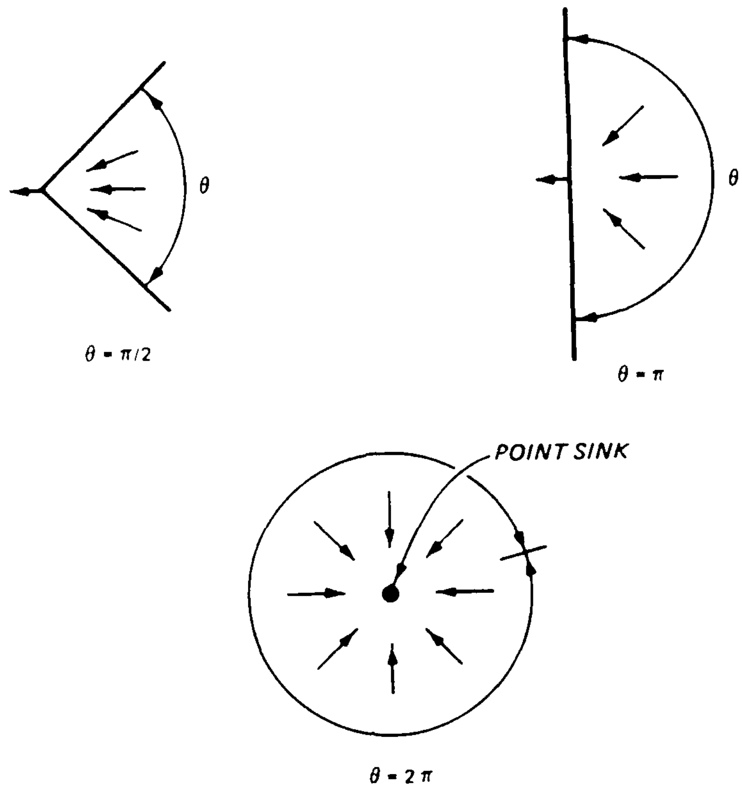

Figure 12. Example withdrawal angles in plan view (from Smith et al. 1987)

61. The physical significance of the effective angle of withdrawal is seen in the figure. For an orifice in a flat plate (equivalent to a port in a vertical dam face), the value of θ was found to equal about 3.14 radians or about 180 deg. Research on ports mounted in a 90-deg corner at the meeting of two vertical flat plates, confirmed that the value was, indeed, about 1.57 radians (Smith et al. 1987). Essentially, if the withdrawal zone is laterally confined, it will expand vertically to compensate. Therefore, the inclusion of the effective angle of withdrawal has provided multidimensionality to the selective withdrawal description.

62. The shape of the in-reservoir velocity profile produced by port operation has been predicted based on empirical descriptions. One of these descriptions was developed by Bohan and Grace (1973) and is given in Equations 6 and 7. Equation 6 relates the vertical position within the withdrawal zone and the density gradient to the relative velocities within the velocity profile. The location of the maximum velocity is predicted through the empirical description in Equation 7, also from Bohan and Grace (1973).

$$\frac{v}{V} = \left(1 - \frac{y\ \Delta\rho}{Y\ \Delta\rho_m}\right)^2 \tag{6}$$

$$\frac{Y_1}{H} = \left[\sin\left(1.57 * \frac{Z_1}{H}\right)\right]^2 \tag{7}$$

where

v = local velocity, fps

V = maximum velocity, fps

y = distance between the center line of the port and the point of interest, ft

Y = distance between the center line of the port and the free limit, ft

$\Delta\rho$ = fluid density difference between the center line of the port and the point of interest, pcf

$\Delta\rho_m$ = fluid density difference between the center line of the port and the free limit, slug/ft^3

Y_1 = distance between the elevation of maximum velocity and the lower limit of withdrawal, ft

H = thickness of the withdrawal zone, ft

Z_1 = distance between the center line elevation of the port and the lower limit of withdrawal, ft

63. In general, adequate research has been done to estimate confidently the velocity profile, and thereby the release water quality characteristics, for simple intake structures with simple near field topographies. The vertical dam face and flush-mounted intake structure at Elk Creek lend themselves to description with the generalized techniques. However, the potential influence of the unusual near field topography on the withdrawal description of the water quality intakes (particularly those nearest the bottom) could not be confidently estimated with the generalized techniques. The hillside, the diversion channel, and the structure itself might have produced impacts. Therefore, the use of a three-dimensional physical model was required for determination of the characteristics of the withdrawal patterns.

Testing procedures

64. Density stratification within the lake, normally resulting from temperature stratification, was simulated in the model through salinity. High-grade salt was added to the water in the flume in varying amounts

increasing with depth to produce density strata. This effect was achieved by filling the flume slowly in layers. The most highly saline waters, which represented the hypolimnion of the reservoir, were put in the flume first. Then, the epilimnion, represented by a freshwater layer was added using a broad-crested weir and very slow inflow rates to inhibit mixing and smearing of the density interface. The stratification pattern was sometimes manipulated at this point by limited mixing to represent more closely a stratification pattern found in the prototype. Exact replication of the density patterns seen in the prototype was not attainable as diffusive mixing and mixing from surface stress could not be completely controlled in the model. Similarity between the model and prototype density patterns was desired, but exact repli-cation was not necessary since multiple density patterns that banded those observed in the prototype were simulated.

65. Once the flume was filled and the stratification was deemed acceptable, the model pool was allowed to stabilize; that is, the currents remaining from the filling and stratification process were allowed to subside. Crystalline dye was usually dropped into the flume to observe the magnitude of the extraneous currents. After the currents had calmed to an acceptable level, the density stratification pattern was more accurately measured.

66. Initially, three samples were extracted from the pool. These usually represented a surface, a median, and a bottom sample. These samples served to relate measurable conductivity and temperature of the samples to known densities. This allowed the computation of in situ fluid density from measurement of temperature and conductivity within the pool. The densities of the samples were measured using a hydrometer. The conductivities and temperatures of the samples were then measured. These tasks were accomplished using either a Digitec temperature probe and Beckman specific conductance meter or a Yellow Springs Instruments (YSI) Model 32FL field conductivity and temperature meter with a model 3417 plastic-encased YSI conductivity cell and a 700 series YSI temperature probe.

67. The probes were attached to a fixed-depth gage. This provided a way of measuring the vertical location of the probes accurately. The probes were then lowered through the pool depth at small intervals (usually 0.2 to 0.5 ft through the significant gradients and up to 1.0 ft otherwise) and the temperature and conductivity were measured. Care was exercised to ensure that the measurement intervals were small enough to describe any sharp density

gradients adequately. The resulting values produced a density profile based on the sample measurements. This process was performed at only one plan view location as the pool was assumed to be homogeneous both laterally and longitudinally. Considering the settling time permitted and the observed in-pool velocities, this was a good assumption. All of the preceding steps were performed prior to releasing any flow through the model.

68. The actual testing was then begun. The selected ports at the face of the structure were secured open. The pumps were primed through freshwater lines and were started simultaneously with the opening of one or more of the flow-controlling ball valves at the end of the water quality system. One or more of the valves in the system were then adjusted to achieve the proper flow rate reading on the flowmeter output. The system was then allowed to reach a pseudo-equilibrium state. An actual equilibrium was not possible as the water surface was slowly dropping and the stratification pattern was slowly changing; however, neither changed significantly during a single test. Reaching this stabilized state usually required only a few minutes.

69. By this time, a stable velocity profile had developed within the pool. Initially, the profile was detected by dropping crystalline dye again. This type of dye left a thin, vertical ribbon of dyed water that was easily tracked. The dye was dropped in front of a fixed grid for vertical reference, and the streak displacement was filmed using a video camera mounted underwater at about the elevation of the open intake port. A video monitor and video cassette recorder were employed to record the dye streak. Each test continued until the dye streak had developed a clear profile with discernible limits of withdrawal. The dye streaks were a reflection of the prevailing velocities in the model pool. This approach worked well for the first few tests. However, extraneous currents caused by the flume filling process, meteorological influences (wind and thermal influx/efflux), and remnants of previous tests often became as large as, or larger than, the withdrawal-induced velocities. Therefore, only under ideal conditions were the dye streaks an accurate representation of the desired velocity profile. Waiting for the coincidence of the proper conditions with which to conduct tests was not considered to be pragmatic. To conserve time and effort, another alternative for describing the withdrawal patterns was sought.

70. The proposed intake structure at Elk Creek closely resembles the test configuration (an orifice in a flat plate) from which the empirical

equations that comprise the generalized selective withdrawal description were developed. Therefore, the shape and maximum velocity descriptions for the Elk Creek structure should not deviate significantly from the generalized description. Also, in the absence of the unusual near field topographic influences, it could be confidently estimated from previous work (Smith et al. 1987) that, for this structure mounted to a vertical dam face, the effective angle of withdrawal would be approximately π radians. The only unknown influence was that of the near field topography on the withdrawal zone. This influence should have been most pronounced at the lowest water quality intakes since they are closest to the reservoir bottom. Therefore, testing was initially concentrated on the lowest intakes.

71. As discussed previously, topographic influences are handled in the selective withdrawal description through the effective angle of withdrawal. Therefore, if the topographic influences were significant, an effective angle of withdrawal other than π (anticipated by the geometry) would be in order. During all preliminary testing, the withdrawal zone encountered interference from the reservoir bottom when the lowest intakes were used. The location of the lower limit of withdrawal was always the reservoir bottom. A reduction in withdrawal angle would, therefore, tend to cause the establishment of a higher upper limit of withdrawal. This would have resulted in the release of less dense water from higher in the pool. Likewise, an increase in withdrawal angle would lower the upper limit of withdrawal, confining the withdrawal zone to the more dense bottom water.

72. It was then considered practical, as a first step, to determine whether or not the topographic influences were at all significant in the selective withdrawal description for Elk Creek. The lowest set of water quality intakes was tested for a variety of discharges and stratification patterns. The withdrawal angle was assumed to be π (i.e., the topographic influences were assumed); and the numerical model SELECT (Davis et al. 1987), which contains the generalized selective withdrawal description, was employed for the same conditions as the model. The SELECT-predicted release density was then compared to the model-observed release density. If the effective angle of withdrawal had been substantially different from the assumed value of π , the differences between the predictions and observations should have been consistent in one direction; that is, if the angle were actually smaller than π , the observed model release densities should have been consistently less

than the SELECT predictions. A converse result would be expected if the angle were actually larger than the assumed π.

Selective withdrawal results

73. Figure 13 gives the SELECT-predicted densities along the horizontal axis and the physical model release densities along the vertical axis. The diagonal line represents perfect agreement between the predictions and observations. Although the results contain errors between the predictions and observations, no consistent errors were demonstrated. About half of the tests produced predicted densities larger than the observations and the other half produced predicted densities less than the observations. From this, it was concluded that the effects of the unusual near field topography on the withdrawal description were not large enough to modify the effective angle of withdrawal significantly from the estimated value of π. Furthermore, if the effective angle of withdrawal for the lowest ports was known to be near π, it could be safely concluded that the effective angle of withdrawal for all of the water quality intakes would also be near π.

74. Instrumentational problems are probably responsible for the errors between the predictions and observations in Figure 13. Keeping all the

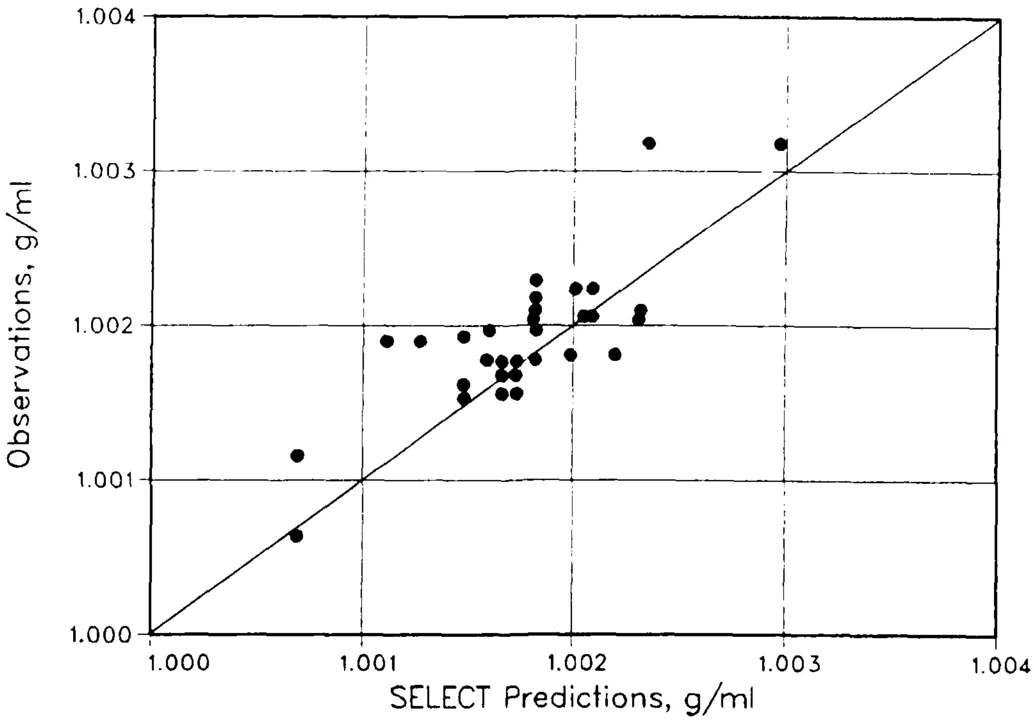

Figure 13. Observed versus SELECT-predicted release densities

equipment, which is normally used in a temperature-controlled environment, calibrated and functioning in often unforgiving weather conditions was difficult at best.

75. The low flows to be released through the water quality system probably contributed to the absence of impact by the topography on the selective withdrawal description. The velocities in the pool were very low with such small discharges. Unusual topographic effects might have been more pronounced at higher flows. However, an evaluation of the errors versus the discharge revealed no substantial trends for the range of flows tested. Although a few larger errors were identified at the lowest discharge tested, the errors appeared to be independent of the discharge. A plot of the discharge versus the density differences between the predictions and the observations is given in Figure 14.

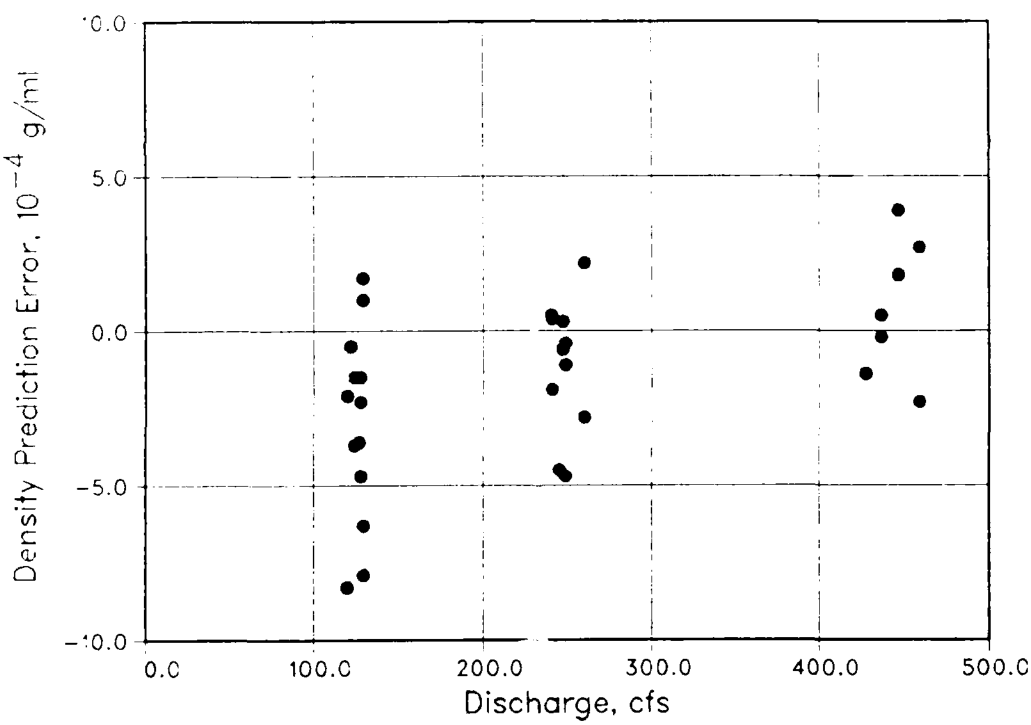

Figure 14. Discharge versus density difference

Simultaneous Multiple Level Withdrawal

76. The second phase of the study involved a more in-depth evaluation of

the blending characteristics of the intake structure. From this evaluation, a description was to be developed that allowed the establishment of gate settings, a priori, to achieve a prescribed downstream temperature target.

77. Phase I results had shown that blending would occur in the model of the proposed intake structure and that, through partial closure of the intakes, the desired flow percentages could be approached. The work that remained in this area was to describe the blending process adequately to produce the desired flows and thereby the desired release temperature (or as close as could be achieved with the prevailing hydraulic and stratification conditions). Development of this description followed a path similar to that of the Lost Creek Lake study (Howington 1989). It was postulated that the blending description would parallel the existing algorithm developed during research (Howington 1988; Howington, in preparation) and would not require extensive modifications for application to Elk Creek. The testing sequences were, therefore, designed to compare the model results with the algorithm predictions.

Unstratified flow testing

78. The factors that control the distribution of flow among open ports in the absence of direct flow control are hydraulic differences among the ports and density stratification influences. Separation of these effects was necessary. Since the hydraulic effects were always present, they were evaluated first. A sequence of tests was conducted in the absence of stratification to quantify the hydraulic differences between the ports. This process required that a relationship be developed between flow rate and head loss for each of the ports. Although all eight water quality intake ports are to be the same size, the close proximity of the regulating outlet structure and a slightly different gate slot for the lowest ports produced a measurable difference between them and the upper six ports.

79. The relationship between head loss and discharge for each port was determined with the physical model. The model pool was first destratified completely using mixing and filter pumps. Then, a single port opening with a specified discharge was established. The water-surface differential between the wet well and the pool was then measured directly using two fixed-mount point gages, one inside the wet well and one outside. The water-surface differential is a direct measurement of the head loss (in feet of water) experienced by water entering the port. An example test is plotted in Figure 15.

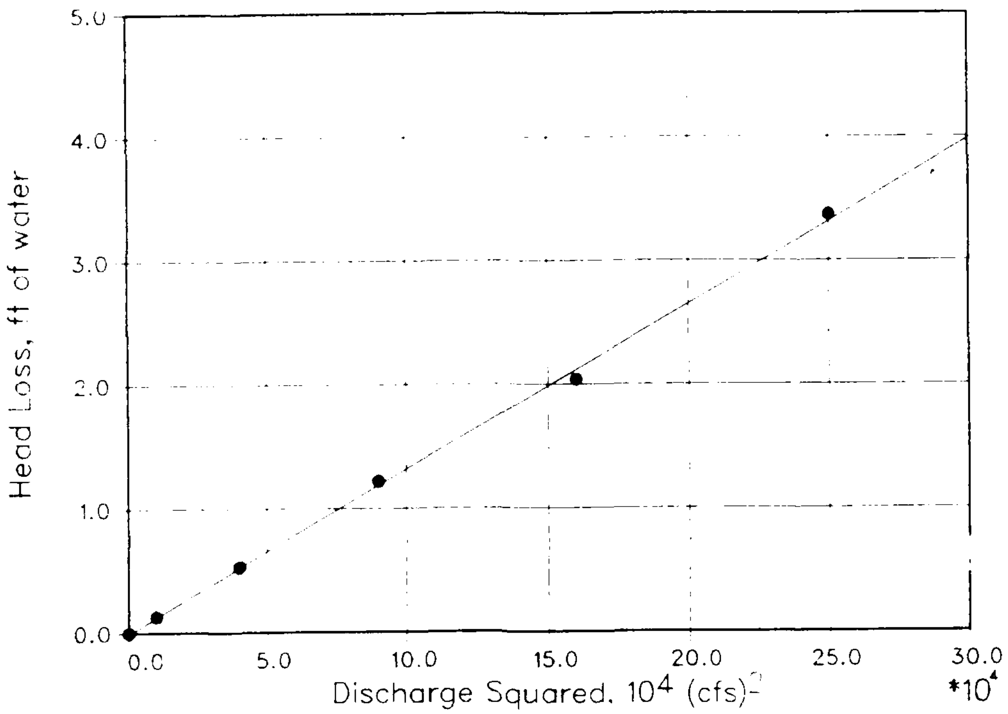

Figure 15. Example discharge squared versus head loss curve

The results indicated that the Darcy-Weisbach formulation, given in Equation 8, which relates the head loss to the velocity squared, was applicable.

$$Hl = k * \frac{V^2}{2g} \tag{8}$$

where

Hl = head loss, ft

k = head loss coefficient

V = average velocity, fps

The independence of the head loss coefficient from factors other than velocity squared was concluded from the linearity of the relationship between the water-surface differential and the squared flow rate (like that demonstrated in Figure 15).

80. Having established that a constant head loss coefficient was applicable for any flow rate for a given port, the relationship between the coefficient and the port opening was desired. Similar tests to that shown in Figure 15 were conducted with several port settings for each flow rate. The resulting relationships between the head loss coefficient and the port opening

was found to be virtually the same for the top three levels of intakes; however, it was slightly different for the bottom level. For each port opening, the loss coefficients for all the flows tested were averaged. These were then plotted against percent port opening. Figures 16 and 17 show these plots and the result of regression analyses to describe these relationships with equations. Equation 9 describes the coefficient versus port opening for the upper three port levels. Equation 10 similarly describes this for the lowest level of ports.

$$k = 0.0000004036*Go^3 - 0.0002198*Go^2 + 0.02445*Go + 0.493 \tag{9}$$

$$k = 0.00000209*Go^3 - 0.000631*Go^2 + 0.05485*Go + 0.21 \tag{10}$$

where Go is the percentage of gate opening.

81. Although some scatter exists among the data, the third-order polynomial curves adequately describe the relationship between loss coefficient and gate opening.

Density stratified flow testing

82. After the hydraulic differences were quantified, the density stratification influences were examined. These tests were conducted much the same as the Phase I tests. The pool was stratified and the stratification measured similarly. Individual port inflow densities were approximated using the SELECT numerical model (Davis et al. 1987). Density impact terms were computed graphically as before.

83. The release quality and quantity were decomposed into individual port flows for comparison to the predicted flows. A computer code containing the blending algorithm was run with the data collected for each test, producing a prediction of the individual port flows. These predictions were compared to the observed port flows from the physical model. The agreement between the predictions and observations was acceptable.

84. A sample plot from one of the tests is given in Figure 18. The longitudinal axis represents total structure discharge; the vertical axis, the percentage of total discharge passing through the upper port. Each curve represents the blending algorithm predictions for a given gate setting and varying total discharge. The symbols represent the model observations; the lines, the predictions. This diagram clearly demonstrates the effects of throttling on flow distribution. It also demonstrates that throttling can,

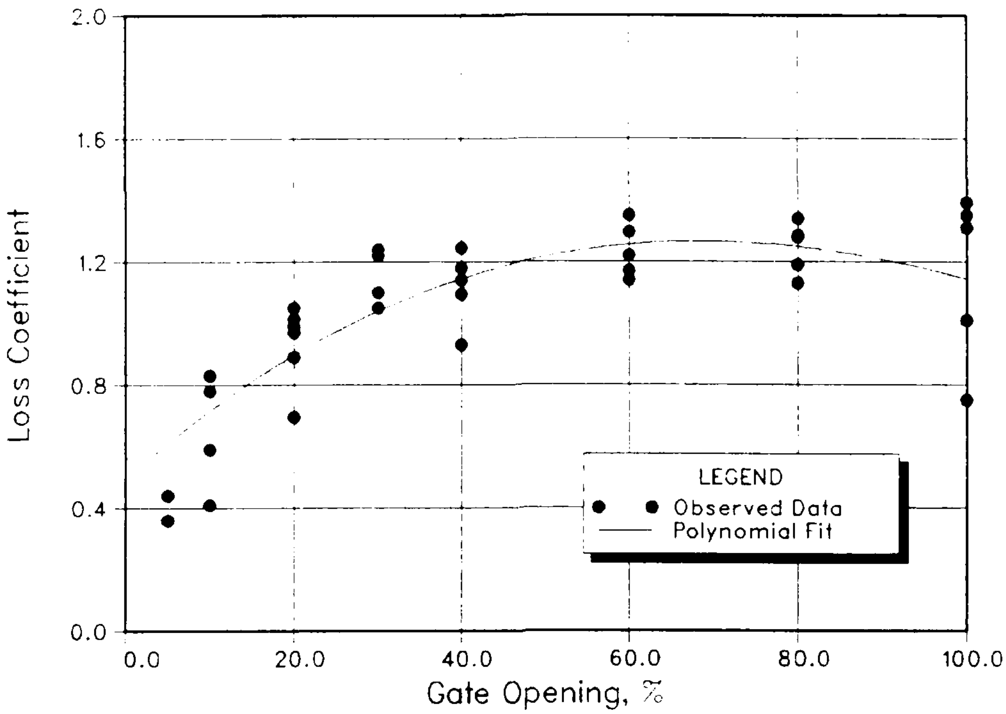

Figure 16. Head loss coefficients versus percent port opening for the top three port levels

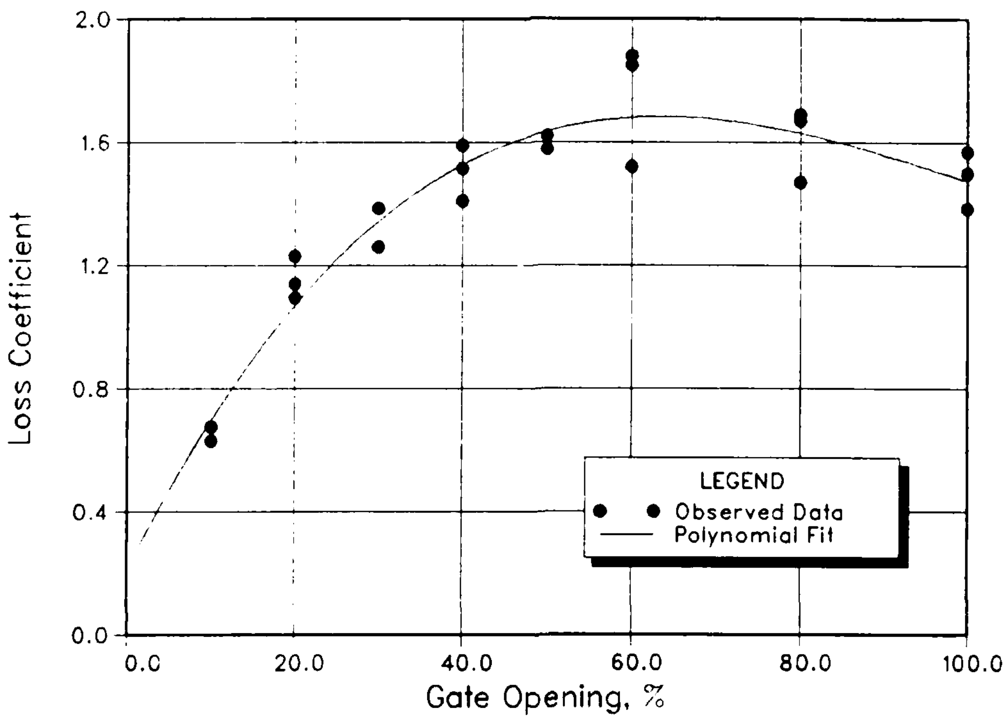

Figure 17. Head loss coefficients versus percent port opening for the bottom port level

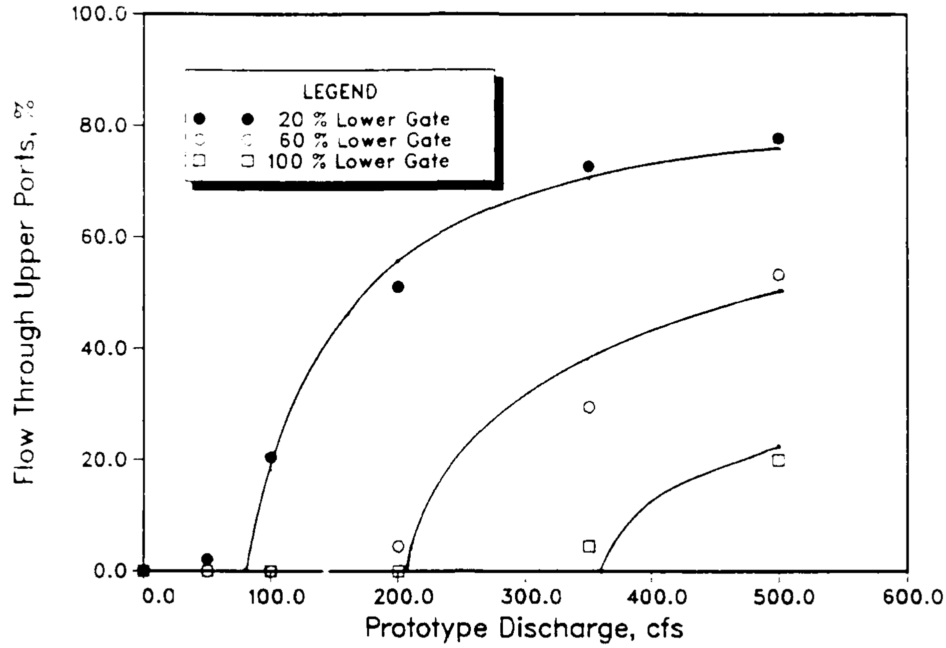

Figure 18. Sample predicted and observed port flows

theoretically, produce any desired distribution of flow among the open ports.

85. No flow through the upper port at very low flows indicates that density impacts were largest at low discharges. This was true for all tests because the density impact term was not flow dependent. However, the other terms in Equation 2 were head loss terms, which increase greatly with discharge. Therefore, the density impact term, although still present in the equation at the higher flows, was overshadowed by the other terms and the flow distribution approached that of the homogeneous density condition (indicated by the lines asymptotically approaching horizontal).

86. Figure 19 displays the results of the stratified flow testing. The longitudinal axis represents the predicted percentage of total discharge through the metered port, and the vertical axis represents the observed percentages. The solid line represents perfect agreement. Deviations are generally small. Most often, the predicted upper port flow exceeded the observed. However, the general agreement between the predicted and observed flows was good with a standard error of estimate of 7.8 percentage points.

87. The results of these efforts include both an accurate selective withdrawal description and an accurate method of computing density influences

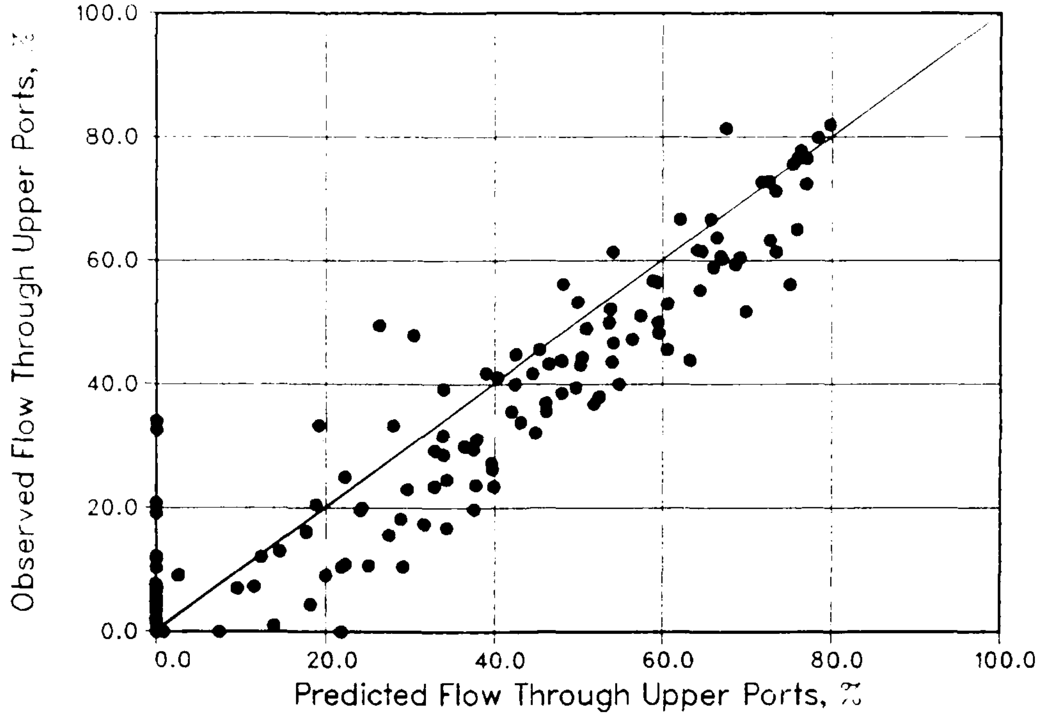

Figure 19. Observed versus predicted flow percentages

on flow distribution. The resulting tool created by coupling these capabilities with the SELECT reservoir withdrawal model provides port designation and gate openings for those ports that will, within the accuracy constraints of the most recent technology available, most closely achieve the desired release temperature for Elk Creek Lake. Required input for this tool, in addition to that for the SELECT model, are head loss coefficients (as computed by Equations 9 and 10) and minimum allowable gate settings.

PART V: SUMMARY AND CONCLUSIONS

88. A 1:20-scale physical model of the proposed single wet well Elk Creek Dam intake structure and near field topography was built and tested to (a) allay concerns over the structure's ability to withdraw water stably simultaneously from multiple levels in a stratified pool; and (b) produce tools for the effective operation of this intake structure with a temperature-sensitive downstream environment. Testing was divided into two phases along these lines. The first phase concentrated on the structure's ability to blend waters of different densities in a hydraulically stable manner within the wet well. The second phase consisted of a detailed investigation of the selective withdrawal and blending descriptions of this structure.

89. The Phase I investigation was conducted and the preliminary results reported to USAED, Portland.* The structure was found to be capable of simultaneous multiple level withdrawal in a variety of stratifications. Density blockage was encountered for many of the test conditions including some of the higher flow tests. However, the use of partial port closure (throttling) overcame the density influences, producing flow from both open levels of ports. Throttling also provided obvious control over the distribution of flow among the open ports, as was expected from previous work. It was discovered that, by throttling, each of the flow distribution/stratification strength scenarios identified by USAED, Portland, in paragraph 40 could be approximated in the model.

90. Also in Phase I, the hydraulic stability of the model was examined. The results of visual and piezometric inspections under various flow and port setting combinations revealed no conditions under which the flow was unstable. Hydraulic blockage conditions were also not producible in the model. In general, the head losses were small. That would be expected with a structure of this size with such a small proposed maximum discharge (500 cfs). No structural modifications were recommended as a result of this phase of the investigation.

91. The Phase II investigation was then conducted with the physical model to further describe the withdrawal characteristics of the structure and

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* Personal communication, 16 May 1986, to Mr. Bill Branch, US Army Engineer District, Portland, Subject: Progress Report, Model Study of Elk Creek.

to quantify the effects of density on flow distribution. The selective withdrawal description produced through the analysis of the model data was straightforward and correlated well with the existing generalized selective withdrawal techniques. A comparison between the mathematical model-predicted release qualities and the physical model observations suggested that no modification to the existing description need be implemented and that the most geometrically logical value for withdrawal angle π be retained.

92. The description of simultaneous multiple level withdrawal likewise followed the previously established trends. A description of the head loss coefficients was developed with an unstratified pool. The coefficients from this work were used to compare the physical model data to the predictions made by the blending algorithm. The results again were good.

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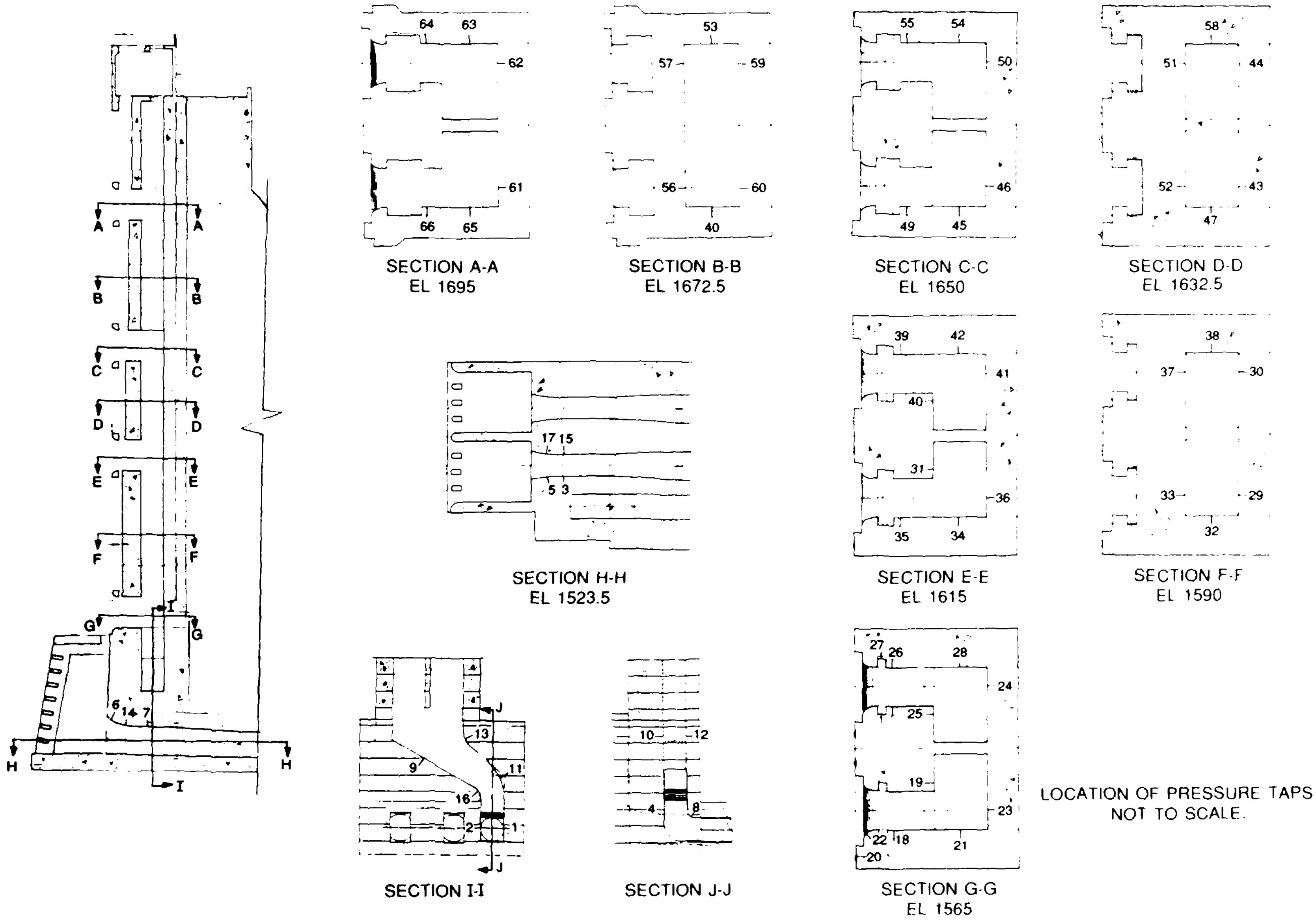

LOCATION OF PRESSURE TAPS
NOT TO SCALE.

PLATE 1